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Dual-parameter modulation improves stimulus localization in multichannel electrotactile stimulation

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Abstract— Among most challenging open issues in prosthetic research is the development of a robust bidirectional interface between a prosthesis and its user. Commercially available prosthetic systems are mechanically advanced, but they do not provide somatosensory feedback. Here, we present a novel non-invasive interface for multichannel electrotactile feedback, comprising a matrix of 24 pads, and we investigate the ability of able-bodied human subjects to localize the electrotactile stimulus delivered through the matrix. For this purpose, we tested conventional stimulation (same frequency for all pads) and a novel dual-parameter modulation scheme (interleaved frequency and intensity) designed to facilitate the spatial localization over the electrode. Electrotactile stimulation was also compared to mechanical stimulation of the same locations on the skin. Experimental results on eight able-bodied subjects demonstrated that the proposed interleaved coding substantially improved the spatial localization compared to same-frequency stimulation. The results also showed that same-frequency stimulation was equivalent to mechanical stimulation, whereas the performance with dual-parameter modulation was significantly better. These are encouraging outcomes for the application of a multichannel interface for the restoration of feedback in prosthetics. The high-resolution augmented interfaces might be used to explore novel scenarios for effective communication with the prosthesis user enabled by maximizing information transmission.

Index Terms — Electrotactile stimulation, matrix electrodes, mechanical stimulation, sensory feedback, spatial localization

1 Introduction

Restoring sensory feedback is a long-standing challenge in prosthetic research [1], [2]. Contemporary myoelectric prostheses respond to electrical muscle activity and thereby restore lost motor functions, but the amputee users do not "feel" their artificial limbs. Apart from a single recent example [3], commercial prostheses do not provide somatosensory feedback to the user. Therefore, the replacement is only partial. This issue is critical since sensory feedback is necessary for the motor control in able-bodied subjects, especially during dexterous activities such as manipulation and grasping [4].

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The topic of sensory feedback in prosthetics has being investigated intensively in recent years (see review papers [5], [6], [7], [8] for a comprehensive overview and [9] for a table summary of different studies). There are sophisticated systems that rely on direct stimulation of peripheral nerves [10], [11], [12], [13], [14], [15], [16], [17], [18] or brain [19], [20], [21] to elicit tactile sensations. These approaches allow feedback to be delivered somatotopically, by activating the same sensory structures that were responsible for the feedback before amputation (e.g., a contact on prosthesis finger feels as a touch on phantom finger). Preliminary results are promising [11], but more extensive studies on humans are needed to understand how to effectively and safely stimulate afferent pathways of the human nervous system to provide clinically usable sensory feedback. Moreover, these approaches are invasive and require a surgical procedure, which may affect their acceptance by prosthesis users.

Non-invasive sensory feedback systems could prove to be an interesting alternative to invasive solutions. The implicit assumption is that it might not be necessary for an artificial system to exactly restore the biological information transmission, provided that an intuitive communication between the prosthetic device and the human brain is established (sensory substitution). The present paper therefore focuses on non-invasive systems for sensory restoration. With respect to previous studies, we focus on increasing the information transfer by associating the stimulation not to a simple physical variable (such as force) but to complex sensations (such as the location of touch).

There is significant body of tactile perception research dating to at least early 1960s investigating the psychometric properties of electrical and mechanical (vibrating and nonvibrating) stimulation. The effect of intensity, frequency, geometry, spatial, temporal, and spatiotemporal coding on the quality and quantity of perception was extensively studied (see eg [22], [23]). There is a body of research on tactile localization through an array of tactors for vibrostimulation [24], [25], [26]. In particular, the ability to localize vibrotactile stimuli was examined at sites around the abdomen [24] and linearly on the forearm [25] with main finding that tactor position counts, in that the percent success rate in localization depends on cutaneous location at which the tactor is placed (comparison among different sites along the forearm [25] and around the abdomen [24]).

Traditionally, the non-invasive sensory feedback systems rely on a few discrete sensing and stimulation units [6], [9]. In a typical approach, a sensor is used to measure a global prosthesis variable (e.g., overall grasping force), and this information is then transmitted to the prosthesis user through a single stimulation unit, which can be a vibration motor or an electrode placed on the residual limb [9], [22]. The feedback variable (e.g., measured grasping force) can be communicated to the user by modulating the parameters of stimulation (intensity, frequency or spatial location). For example, the higher the grasping force, the higher is the stimulation intensity delivered to the subject, which leads to a stronger tactile sensation [23]. The user needs to learn to associate the elicited sensation to the measured variable. This can be a challenging task, and typically, only few levels of grasping force/hand aperture can be reliably communicated [11], [27], [28], [29].

The contemporary methods for feedback restoration are therefore characterized by a limited information transfer. To mitigate this drawback, feedback interfaces comprising several stimulation units have been proposed. In principle, multichannel stimulation could allow to better exploit the inherent potential of the human skin as the feedback stimulation can be distributed over a large skin area (spatial coding). For example, an array of vibration motors has been previously used to communicate hand aperture [30] and grasping force [31] feedback. Advanced interfaces for electrotactile stimulation integrating multiple electrode pads have also been recently tested [32]. In [33], an electrode array integrating 16 pads placed circumferentially around the forearm was employed to deliver force feedback from Michelangelo Hand prosthesis. A matrix electrode with 4 x 8 pads has been used to transmit tactile data recorded by an electronic skin to the subject forearm [34]. The tactile data recorded by four neighboring taxels were fused and delivered through a spatially-congruent electrode pad. We demonstrated that the subjects were able to recognize the dynamic stimulus moving along the matrix electrode. Here, different shapes (geometries and letters) were presented using conventional stimulation with a fixed frequency (corresponding to “same-frequency condition” of the present study). The spatial coding and artificial skin were used in another experiment [35] where the stimulation was delivered using fixed frequency through a 4 x 2 arrangement of conventional self-adhesive large concentric electrodes. Preliminary experiments on the ability to localize touch delivered to the artificial skin by identifying the elicited electrotactile sensation have been performed in two subjects. These studies have shown the potential of multichannel electrical stimulation, however, they also pointed out that spatial localization is a challenging task, especially considering the low density of tactile receptors on the human forearm (stimulation target in hand prosthetics).

In this study we aim at assessing the reliability of information transmission when using non-invasive interfaces with many stimulation points. We use a novel, compact electrotactile interface in the form of a dense 6x4 electrode matrix printed on a flexible substrate (11 x 5 cm^2). An electrode matrix is particularly suited for transmitting tactile information from an artificial skin covering the prosthetic device, as demonstrated in our previous study [34]. However, a compact interface in which the pads are closely spaced can be a challenge when the subject needs to localize the tactile stimulus. Good spatial localization is important for transmitting an accurate tactile information to the user of a prosthesis (e.g., contact location) or when conveying other prosthesis variables using spatial coding (e.g., aperture [30]). Therefore, in this study we investigate if the quality of localization can be improved by exploiting the flexibility in parameter modulation provided by an electrotactile interface. The electrotactile stimulation allows independent modulation of intensity and frequency, while these parameters are intrinsically coupled in commonly used vibration motors [36]. We have therefore developed and tested a dual-parameter modulation scheme (intensity and frequency) to assist the subject in correctly identifying an active pad within the matrix. Furthermore, for the first time, the performance of a matrix electrotactile interface is compared to that of the human skin being mechanically stimulated over analogous contact areas.

2 Materials and Methods

2.1 Stimulation Setup

The setup is illustrated in Fig. 1. The MaxSens stimulator prototype developed by Tecnalia Research and Innovation generates electrostimulation profiles to be transmitted to the participant through a matrix of electrodes applied to the forearm. The stimulator comprises a single stimulation unit that can generate continuous, biphasic, symmetric and rectangular current pulses [32]. The biphasic waveform has been preferred to monophasic pulses due to less skin reddening and more comfortable sensations [22]. The waveform is presented in Fig. 2, with all

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the relevant stimulation variables marked on the plot. The stimulation unit is connected to a matrix electrode through an analog multiplexer, which can distribute the pulses in time and space over the matrix electrode, thus providing a multichannel stimulation interface. The MaxSens is fully programmable and the stimulation parameters can be modulated online by sending text commands from the host PC via Bluetooth connection. The adjustable stimulation parameters are: (1) the current amplitude in the range 0-5 mA (0.1 mA increments), (2) the pulse width (range 50-1000 µs, 10 µs increments), and (3) the stimulus frequency (1 - 400 Hz, 1Hz step). It is worth noting that electrode-skin impedance is a relevant factor that can greatly affect user perception of the electrotactile stimulus. A recent study [37] proposed a solution in which the stimulation amplitude was regulated in real-time based on measured impedance at the skin-electrode interface. In our study, to ensure stable electrode to skin contact we used fresh hydrogel pads in each experimental session. Moreover, current regulated stimulation has been chosen to minimize the influence of capacitive effects at the electrode-skin interface and ensure consistent activation of the cutaneous nerves [38]. This guarantees that the nerve stimulation and thereby the elicited tactile sensation is not altered throughout the experiment due to changes in skin moisture and hydrogel adhesion.

In this study, the stimulator was connected to two custom designed flexible matrix electrodes developed by Tecnalia Research and Innovation. Each matrix electrode consists of 16 oval units (pads) with the longitudinal radius of 5 mm and transverse radius of 3 mm. The units are arranged in a 6 x 2 grid, with 4 lateral pads (two at each side). The center-to-center distance between two adjacent pads is 20 mm in the longitudinal and 14 mm in the transverse direction. Each pad is made of Ag/AgCl conductive layer and conductive hydrogel circular elements of 5-mm radius (AG730, Axelgaard, DK) are added on top of each pad to ensure good electrical contact between the pad and the skin. An insulation coating is distributed on top of the electrode, excluding the pad areas. The pads on the matrix were designated as cathodes whereas a single self-adhesive electrode (ValuTrode Foam [39]) placed on the dorsal side of the forearm acted as the common anode (Fig. 1). The ValuTrode bottom electrode is made of glycerin, water and poly(acrylate) copolymer. It is a well-known product on the market, recognized for its durability and multiple applications to the skin. We used the rectangular ValuTode electrode with size 5 x 9 cm^2.

For the experiment, the two flexible matrix electrodes were overlapped in their central part in order to obtain a rectangular array including 6 x 4 pads (Fig. 1), distributed over a total area of 11 x 5 cm^2. Hereafter, we will refer to this rectangular array as “the matrix electrode”. The 4 lateral pads (two at each side) were not used in the present study. The matrix electrode was placed on the volar side of the subject forearm, while the common electrode was positioned on the dorsal side.

This part of the forearm presents higher tactile sensitivity and acuity. The electrotactile interface has been designed so that the spacing between the pads is higher than the spatial discrimination threshold on the forearm [40] while the number of pads is still sufficient for a flexible mapping of prospective feedback variables. For example, for an intuitive spatial mapping between contact on the prosthesis and forearm stimulation, the four columns of the matrix could be associated to the four fingers (4 x 5) and the thumb could be represented on the remaining row (4 x 1).

2.2 Electrode Placement

The subject sat comfortably on a chair in front of a table. The forearm of the non-dominant arm (always left, as all participants were right-handed) was placed on the table surface, with the volar side oriented upwards. The subject was asked to remove watch or rings (hand was free from any accessories). The skin was preliminary prepared by moisturizing with a water-soaked cotton cloth to enhance the attachment of the electrodes and improve electrical conductivity.

The overlapping electrodes were placed on the volar side of the subject forearm. Particular care has been taken for electrode placement and the same procedure has been used for all the tests, to make results comparable for different participants and for same participant over different trials. The columns were aligned with the four fingers and a reference point for electrode positioning on the longitudinal direction was associated to the intersection of two specific muscles, as indicated in Fig. 3. In particular, the intersection between two superficial flexors, i.e. the palmaris longus and the flexor carpi ulnaris muscles has been used as the reference position for a specific pad (number 22). The indicated position was identified by asking the participant to close the hand and contract the muscles of the forearm. The electrodes were wrapped by a bandage to prevent movement and improve contact.

2.3 Participants

The main experimental campaign involved eight able-bodied volunteers (2 females, 6 males, 35±8 years). The experimental study has been approved by the Regione Liguria Ethical Committee (approval ID 172REG2016). An informed consent form was signed by each participant prior to the experiments.

2.4 Experimental Procedure

The main aim of the experiments was to assess the subject ability in identifying the location of the electrotactile stimulus delivered through the matrix electrode. This was compared to the quality of localization when the mechanical stimulation was applied to the skin. To foster attention and concentration, a silent environment was chosen to avoid any distraction for the participant. To maintain alertness and minimize adaptation[1], the subjects were always given sufficient rest during the experiments [42], [43]. Break between the trials was around 3-4 minutes. In the second session, break between conventional electrical

[1] Adaptation has been defined for vibrostimulation as consisting of two related, but separable phenomena [4~~12~~]: 1) an increase in threshold due to prolonged exposure to a stimulus and 2) a decrease in intensity of a prolonged stimulus over time

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and mechanical stimulation was at least 5 minutes. After that period, the participant was asked if she/he needed a longer break. In case of affirmative response, we added 5 more minutes of rest.

The experiment was divided into two sessions performed in consecutive days. The electrical stimulation (Fig. 4) was tested using two coding schemes: 1) a "conventional" approach with uniform frequency (50 Hz) for all pads (hereafter denoted as same-frequency condition) and 2) a dual-parameter modulation of intensity and frequency, interleaved across the electrode columns (hereafter denoted as interleaved stimulation). The main idea of the latter approach was that additional cues (parameter modulation) would assist the subject in recognizing the location of the active pad. In this scheme, the pads within the columns 1-4 were activated at the frequencies of 10, 400, 10 and 400 Hz, respectively. In addition, the stimulation at 10 Hz was delivered at a lower intensity compared to 400 Hz. Therefore, the frequency and intensity were interleaved across columns of the matrix. The specific frequencies and intensities were determined through pilot tests (see Sect. 5). The interleaved stimulation was tested in the first session, and conventional electrical and mechanical stimulation in the second session. Each experimental session lasted ~1-1.5 hours and this short duration precluded fatigue and distraction of the participant.

In the second session, the electrical stimulation was tested first and the mechanical was tested next (Fig. 5). When electrodes were removed, the position of the pads was still clearly visible via skin reddening. The experimenter therefore marked the position of each pad by using skin-friendly marker. A rubber indenter (radius 4mm, contact area of approximately 8-10mm, diameter ~ same size of the pad) was used to mechanically stimulate the skin of the participant (inset in Fig. 5b).

Each stimulation modality (interleaved, same-frequency and mechanical) was tested using the same experimental protocol comprising three phases: intensity adjustment, training and testing.

Intensity adjustment. The intensity of electrotactile stimulation was adjusted to produce localized and clear sensations that were not uncomfortable. We focused on these characteristics because we assumed that they are most important for localization. Due to time constraints we did not evaluate the sensation quality, but this has been investigated previously in the literature (see eg [44]). For electrotactile conditions, the participant was first asked to define the intensity of the stimulation of each pad for clear perception, avoiding any discomfort. For this purpose, the stimulation intensity was increased gradually (steps of 0.1 mA) and the participant was asked to report when a clear sensation (mean ± standard deviation across all pads and all subjects: *1.41 ± 0.38 mA*) was achieved. Then, the pad was activated/deactivated few times and the subject was asked to confirm that the sensation is indeed clear. If not, the intensity was increased for one step and the test was repeated. Due to the large number of stimulation pads (24), this procedure had to be performed only once per pad. This was nevertheless sufficient since the aim was not to reliably detect sensation threshold but to elicit sensation that can be clearly felt. The pads were activated in a systematic way, column by column. Inside each column, adjacent pads were not activated sequentially: instead, a specific order was chosen to minimize the decrease of intensity over time, due to a prolonged stimulus (same order for all columns, referring to column 1 in Fig. 4b: 1-3-6-4-2-5). Whenever numb feelings were reported, strongly affecting the possibility of localizing the stimulus as the sensation spread over to the whole forearm, the electrode array position was slightly adjusted.

In the case of interleaved stimulation, the experimenter additionally needed to adjust the intensities for the 10 Hz and 400 Hz stimulation. To set the low stimulation intensity for 10 Hz, the subject was asked to look for "low but clear" sensation (mean ± standard deviation across all pads belonging to columns 1, 3 and all subjects: *1.47 ± 0.55 mA*). These values (level 1) were commonly associated to 1-2 steps above the sensation threshold. To set the higher stimulation intensity for 400 Hz, the subject was asked to look for "high but not painful" sensation (mean ± standard deviation across all pads belonging to columns 2, 4 and all subjects: *1.15 ± 0.26 mA*), typically stopping 2-3 steps above level 1. After setting the intensity values for the two frequencies, the experimenter let the participant experience the sensations by moving the active pad across different columns, and small adjustments were allowed.

The intensity of the mechanical stimulation was preliminarily tuned for the stimulation to be clearly perceived by the participant. In any case, preliminary studies showed that there was no relevant difference in localization for different intensities of the mechanical stimulation.

Training. After defining stimulation intensities, a training session was performed for the participant to familiarize with electrostimulation and build a mental mapping between the experienced sensation and the position of the stimulated pad. For that, a sketch of the matrix electrode including the real-size 24 numbered active pads was placed on the table adjoining the forearm, preserving spatial correspondence with the matrix electrode (Fig. 4).

The subject was first trained by experiencing sequential stimulation over each column from top (wrist) to bottom (elbow), while the experimenter orally reported the pad number. Here the participant knew in advance which column and pad would be stimulated and he/she was expected to associate felt sensation to the pad location (number).

In the second training stage, the column was known, but the pads within the column were stimulated in random order. The participant guessed the pad number and then the experimenter provided verbal feedback about the correct answer (reinforced learning).

The total duration of training phase was approximately 15 minutes.

Testing. During testing, the task for the subject was to identify the active pad, and no feedback was provided about the correctness of the guess. The single pads were activated in a pseudorandom order so that each pad was presented two times (48 stimulations). The participant

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was asked to identify the activated pad, by indicating its number or identifying its position over the sketch. In few cases, the subject could not decide on the location, and this was registered as a "missed sensation".

In the training and testing phase during electrical stimulation, the participant was allowed to freely direct the look from the forearm to the sketch and back (Fig. 4a). Our approach was motivated by the fact that in the clinical application of this interface, e.g., during training of electrotactile feedback and even during prosthesis use, the subject will be able to look into his/her residual limb/prosthesis. In any case, there was no visual information related to the stimulation, and the electrode matrix was fully covered with white medical bandage. Nevertheless, this type of visual contact can assist the spatial acuity through the visual enhancement of touch [45]. During mechanical stimulation, a screen was placed between the participant's forearm and the sketch of the matrix electrode to prevent the participant having visual cues to identify the stimulation location (Fig. 5).

In all modalities, the duration of the stimulus delivered to the subject was 2 s. In both conventional and interleaved stimulation modalities, the pulse width and inter-pulse delay were set to w = 200 µs and d = 1 µs (Fig. 2), respectively. The delay between a positive and negative pulse is fixed by construction of the stimulator, and therefore it cannot be adjusted. Considering that it is not possible to exhaustively test the parameter space, the pulse width was set heuristically, based on previous experience [32]. The chosen pulse width allows for good control of tactile sensations in most of the subjects when using amplitude modulation, i.e., a reasonable range between detection and pain thresholds.

3 Data Analysis

The main outcome measure was the success rate (SR) in locating the stimulus. This included the identification of the exact pad at which the stimulation was delivered. However, our intended application is in prosthetics, where small errors can be often tolerated. Therefore, the SR was computed also for pointing to the first neighbor around the correct pad (one-position error) and to the pad within the same column as the correct pad (correct column). The latter (correct column) is of interest when mapping prosthesis variables to the electrode pads, since mistaking the column could represent a much larger error (see Sect 5).

The SRs were computed per subject for each specific stimulation modality (mechanical, same frequency, and interleaved stimulation). The SRs of all subjects were then averaged to obtain the overall mean SR and its standard deviation. The results were reported as mean ± standard deviation in the text and figures.

The data were tested for normality using Kolmogorov-Smirnov test. In all cases, the tests indicated normal distributions, and therefore one-way repeated measure ANOVA was used to assess statistically significant differences at the level of the group followed by Tukey's honestly significant difference test for post hoc pairwise comparison. One-way ANOVA tests were used to compare the success rates in recognizing the specific pad or column across stimulation modalities. The threshold for the statistical significance was adopted at $p < 0.05$, and the statistical analysis was conducted in Matlab R2017b (MathWorks, US).

4 Results

Fig. 6 shows the performance for individual subjects across stimulation modalities. The bars represent the SR in (i) correctly identifying the right pad (light blue), (ii) wrongly identifying the pad but pointing to the right column (orange), (iii) wrongly identifying the pad and the column (grey). The variability across subjects is noticeable for mechanical stimulation.

The summary results, i.e. overall SRs, are shown in Fig. 7. In general, pad recognition was not an easy task for the subjects (Fig. 7a). The overall SR for the mechanical stimulation was 17±9%. The electrotactile stimulation using the same frequency for all pads (50 Hz) was characterized with a similar SR (21±4%). Therefore, the same-frequency electrotactile stimulation provided comparable quality of spatial localization to that of the mechanical stimulation. However, with both modalities, the performance was still substantially better than pure chance, where the subject would simply randomly select one of the pads (1/24 ~ 4%).

Importantly, the SR for the electrotactile stimulation that used the interleaved frequencies and intensities was significantly better (38±9%) compared to both mechanical ($p < 0.001$) and the same-frequency electrical stimulation ($p < 0.001$). The performance almost doubled with the interleaved stimulation scheme. Therefore, the dual-parameter modulation substantially improved the subjects' ability to correctly localize the elicited tactile sensation.

The summary performance in localizing the stimulus up to an error margin around the active pad is reported in Figs. 7b-d. Fig. 7b gives percent of trials in which the subject pointed to a correct pad or its immediate neighbor within the same column (one-position, within-column error tolerance). Fig. 7c is a percent of trials in which the subject pointed to a correct pad or any other pad that belonged to the same column (within-column error tolerance). Again, the SRs in the case of one-position error (Fig. 7b) for interleaved stimulation (70±11%) was significantly higher than for the same-frequency electrical (42±6%, $p < 0.01$) and mechanical stimulation (45±20%, $p < 0.01$). If a small localization error can be tolerated, the interleaved stimulation can therefore lead to a very good performance (e.g. SR up to 96% for subject P6). More generally, with the interleaved stimulation, the subjects could reliably detect the right column (Fig. 7c). The success rate for this modality was significantly better (80±7%) than for the same-frequency (60±5%, $p < 0.01$) and the mechanical stimulation (59±21%, $p < 0.01$). Finally, Fig. 7d reports for all modalities the percent of trials in which the subjects pointed to a correct pad or its immediate neighbor, regardless of the column. This figure further emphasizes the equivalence of mechanical stimulation (SRs: 63±21%) and same-frequency electrostimulation (SRs: 64±9%). The interleaved coding leads to a higher average SR (~79±8%), though this time there was no statistically significant difference with the other two modalities.

The overall success rates for the recognition of individual pads of the matrix electrode in each of the stimulation modalities are show in Fig. 8b (mechanical), c (same-frequency), and d (interleaved stimulation). The figure once again demonstrates that the interleaved modality is the technique which allows for the best recognition of single pads. With mechanical and same-frequency stimulation, there is a trend that the pads on the borders of the electrode area are more successfully recognized compared to the inner pads. In the case of interleaved stimulation, the SR increases for most of the pads and some inner pads reach comparably high SRs.

5 Discussion

We have investigated if the modulation of additional parameters (frequency and intensity) can improve the spatial localization of the electrotactile stimuli. In addition, the electrotactile localization was compared to that of mechanical stimulation, since the latter is commonly used to evaluate the spatial acuity of the skin. In addition, the electrotactile localization was compared to that of mechanical stimulation. This was done to compare a method for sensory substitution (electrical stimulation) with the stimulation as it is typically experienced in daily life, i.e., someone/something touching the skin. It would be also interesting in the future to compare the electrical stimulation with vibrations, which is an alternative method for sensory substitution.

The first important conclusion of the study is that the electrotactile stimulation delivered conventionally, using the same frequency for all the pads, resulted in a similar performance as the mechanical stimulation. The electrotactile stimulation is non-specific and activates a combination of mechanotactile receptors. In addition, the electrical current spreads in the tissue, especially in this configuration where the common electrode is positioned outside of the integrated matrix. The fact that the electrical and mechanical stimulation performed similarly is an encouraging outcome for the application of multichannel interfaces with significant number of pads to the feedback restoration in prosthetics.

The second important conclusion is related to the fact that the electrical stimulation has an intrinsic potential, namely, the flexibility in parameter modulation, which can be used to increase the reliability of information transmission to the subject. The present experiment has demonstrated how dual-parameter modulation can be used to substantially improve the performance in spatial localization of the elicited tactile sensation. The subjects were more successful in identifying the stimulation location using the interleaved stimulation modality compared to other modalities both when locating the correct pad (Fig. 7a), or when accepting (small or large) errors within the right column (Fig. 7b and 7c).

This means that an electrotactile interface can be used to equip a prosthesis user with an artificial tactile sense that can overcome some limitations of the direct mechanical stimulation (e.g., low-density of receptors and thereby poor spatial localization over the forearm). This is a unique advantage of electrical stimulation because the parameters can be independently modulated. In vibration motors, for example, the parameters are often mechanically coupled [42], [46] and in modality matched stimulation there is often only one parameter to modulate (e.g., the pushing force [47]).Since the aim of the present study was to improve localization, we decided to exploit both frequency and intensity (dual-parameter modulation) to make the distinction between the columns as clear as possible. However, in the present study, it cannot be determined how much each of the parameters individually (frequency versus intensity) affected the localization. This question could be investigated in the future by systematically testing combinations of intensity and frequency using factorial experimental design [48] to assess the main effect as well as the interaction between the stimulation parameters.

The "wining" modulation scheme was determined through extensive pilot tests. For example, one approach that has been tested was to associate different stimulation frequencies to each column, e.g., 5, 10, 20, 50 Hz for columns 1, 2, 3, 4. Different combinations of frequencies have been evaluated but the approach was not effective. Therefore, using only frequency modulation did not improve the localization. Finally, the interleaved frequencies with substantial gap were selected (10 vs 400 Hz), and the modulation of frequency had to be complemented with the interleaved intensity, in order to further increase the contrast between the columns. The frequency of 400 Hz was chosen as this was the maximum of the stimulator, but it is likely that the results would be similar with other high frequencies as well (e.g., 10 vs 100 Hz), as the elicited sensations are similar.

The fact that different frequencies were used in the two conditions (same-frequency versus interleaved) might have in itself affected the localization, although for vibrostimulation this effect seems not to be substantial [25], [49]. This could have been addressed by testing two same-frequency conditions (with 10 Hz and with 400 Hz). However, this was not feasible due to time constraints and therefore we have opted for a single (in-between) frequency from a range that is conventionally used [42]. In particular, in a past publication [50] we have actually shown that higher frequencies than 25 Hz and above up to 100 Hz are preferred for sensory feedback.

The lack of randomization is a limitation of the present study that was caused by technical constraints. However, it is unlikely that this has affected the results because we assume that the adopted order was in fact less favorable for the novel modality (dual-parameter modulation). The interleaved stimulation was tested in the first session and the same-frequency and mechanical stimulation were assessed in the second session, and yet the best results were obtained with the interleaved stimulation. Therefore, dual-parameter modulation resulted in the best per-

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formance although the participants were not yet acquainted with electrotactile stimulation. Nevertheless, the potential impact of familiarization and training remains an assumption that was not tested explicitly in the present study.

The enhanced capability of distinguishing the single pad inside the column when using dual-parameter modulation might enable high-resolution contact localization. For example, the proposed high- resolution interface can be used to transmit high-resolution information on contact position or contact mechanics (e.g. force distribution) which might be required for advanced tasks such as dexterous manipulation. For that, the multichannel interface is to be combined with the multichannel sensing systems including several sensors on fingers and palm, such as electronic skins developed in robotics but now increasingly considered for prosthetic applications [34].

However, a drawback of this method is that the spatial localization is improved at the expense of utilizing the two additional stimulation parameters (intensity and frequency). Therefore, they cannot be used anymore to convey feedback information through parameter modulation, as proposed in other approaches (e.g. increasing frequency/intensity to indicate higher grasping force and/or aperture [27], [32], [33]). However, the "intensity variables" can still be represented through a spatial code e.g. force magnitude could be transmitted through the location of the stimulation, as for example in [31].

These preliminary experiments have to be enriched with further exploration focused on tuning the stimulation parameters to reliably convey desired feedback information while maintaining the spatial acuity. A large body of literature investigating how stimulation parameters affect spatial performance (see eg [22], [23], [25]) can be used as a guideline for this exploration.

Final translation into prosthetics implies the integration of the stimulation interface into the socket (in the same way EMG electrodes are currently integrated). One possibility would be to produce the electrodes using conductive silicone so that they are an integral part of the silicone liner.

In recent studies, transcutaneous electrical nerve stimulation has been used to provide somatotopic sensory feedback non-invasively (e.g. [51], [52], [53], [54]). With this approach, referred sensations occur in the phantom hand, which is good for prosthesis embodiment and can facilitate contact localization. The present study relies on electrotactile stimulation that normally does not elicit somatotopic feedback (if there is no phantom representation on the residual limb [55]). Nevertheless, we still do not know how training affects the feedback integration into motor control. It might be that with a long term training even non-somatotopic feedback becomes integrated and processed subconsciously, as suggested in [56].

The role of training is certainly crucial for the feedback interface with that many channels to be usable in the real application, especially when combined with prosthesis control. Importantly, there are encouraging results in literature showing that even a relatively short training can be powerful. In [32], a subject has reached a success rate > 90% in localizing 16 pads of an array electrode after only 2 hours of training. We believe that such training can substantially decrease the initial cognitive effort, though this needs to be tested in future studies.

Overall, the usability and acceptance of the proposed matrix interface is still to be investigated.

The next step in this research will be to investigate how well the subjects could perceive several electrotactile stimuli that are delivered simultaneously or sequentially along the columns (two or more active pads). If the subject could identify the active pads in each column, even when they are activated at the same time, this would allow transmitting several levels of different prosthesis variables concurrently. How many channels of feedback information the patient could interpret and exploit simultaneously depends likely on many factors, such as subjective aptitude and motivation, sensory information encoding, and training and experience. Determining the effective bandwidth of this compact multichannel feedback interface is indeed an important point for future research.

6 Conclusion

The present study assessed the subject ability to localize electrical stimuli delivered through a compact matrix electrode with many pads. The results demonstrated that conventionally applied electrotactile stimulation (single frequency) can reach similar performance in tactile acuity as mechanical stimulation. With a novel dual-parameter modulation scheme, the electrotactile interface provided higher discriminability than the mechanical stimulation. This is an important outcome for the provision of sensory feedback in prosthetics, as it implies that an electrotactile matrix interface can be used to transmit reliable high-fidelity feedback from the prosthesis, by exploiting the flexibility in spatial and parameter modulation characteristic of electrotactile stimulation.

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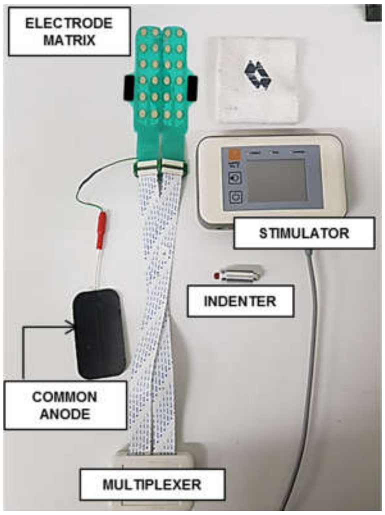

FIGURE 1. Experimental setup. The indenter is used for mechanical stimulation, while all other elements are used for electrotactile stimulation experiments.

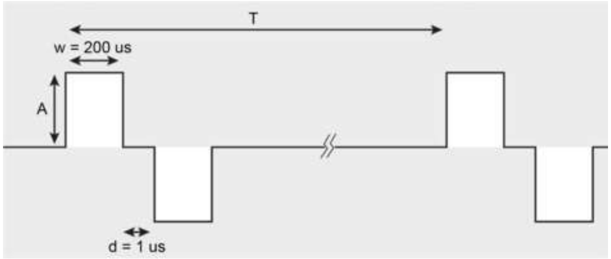

FIGURE 2. Typical stimulation waveform. Notation: A – pulse amplitude; w – pulse width; d – inter-pulse delay; T – inter-pulse interval (pulse rate = frequency = 1/T).

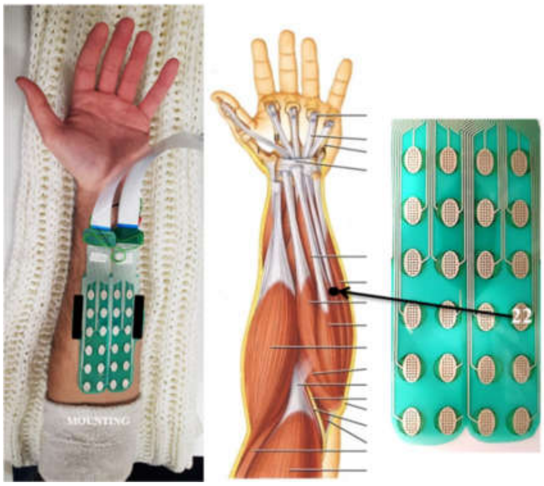

FIGURE 3. Reference position for matrix electrode placing is indicated by a black dot: it corresponds to the intersection between two superficial flexors, i.e. the palmaris longus and the flexor carpi ulnaris muscles. Reference pad for that position is number 22.

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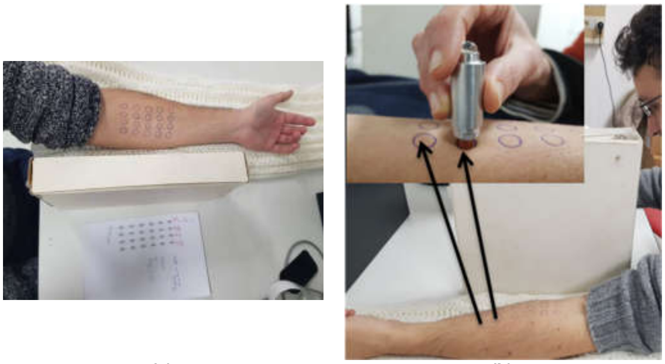
(a)

(b)

FIGURE 4. (a) Electrostimulation tests: a sketch of the matrix electrode (4 columns, 6 rows) is placed on the table next to the forearm. (b) Spatial correspondence between the matrix electrode and the geometrical arrangement of the pads in the sketch is preserved.



(a) *(b)*

FIGURE 5. Experiments with mechanical stimulation. A screen is placed between the participant's forearm and the sketch of the matrix electrode. (b) Top view. (b) Side view.

(a)

(b)

(c)

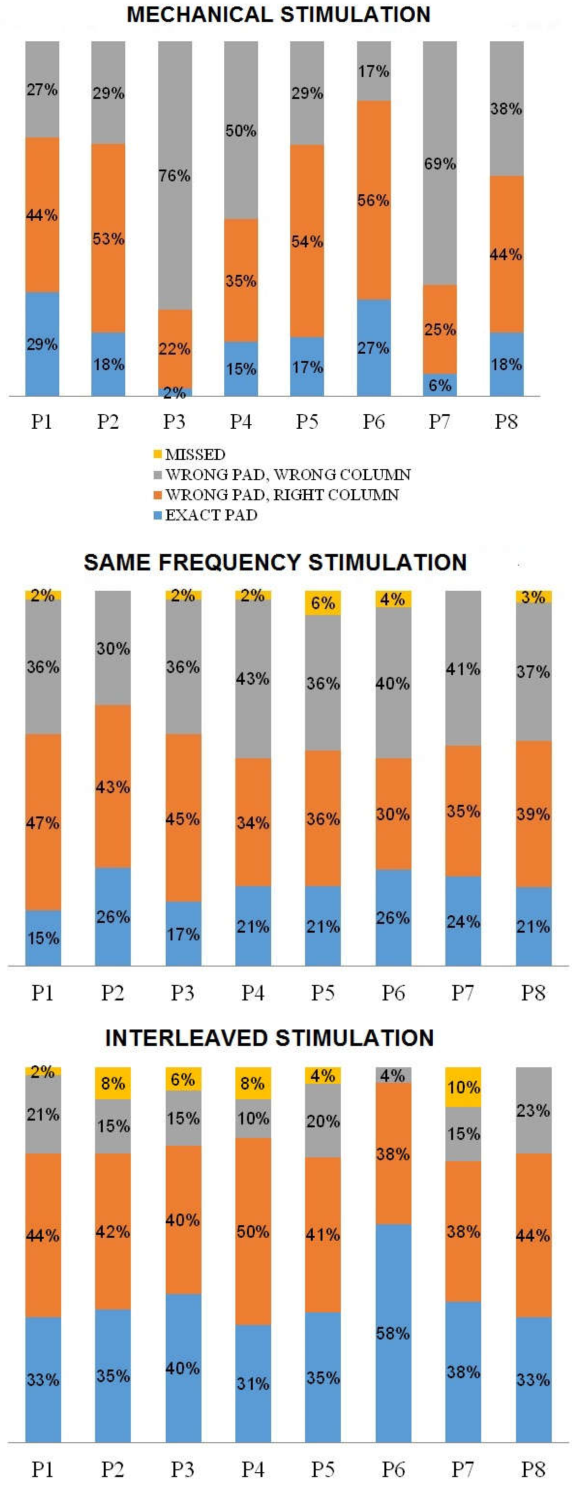


FIGURE 6. The results for individual subjects (P1-P8). Reported percentages are associated to identifying the right pad (light blue), missing the pad but addressing the right column (orange), missing the pad and the column (grey), no answer (yellow).

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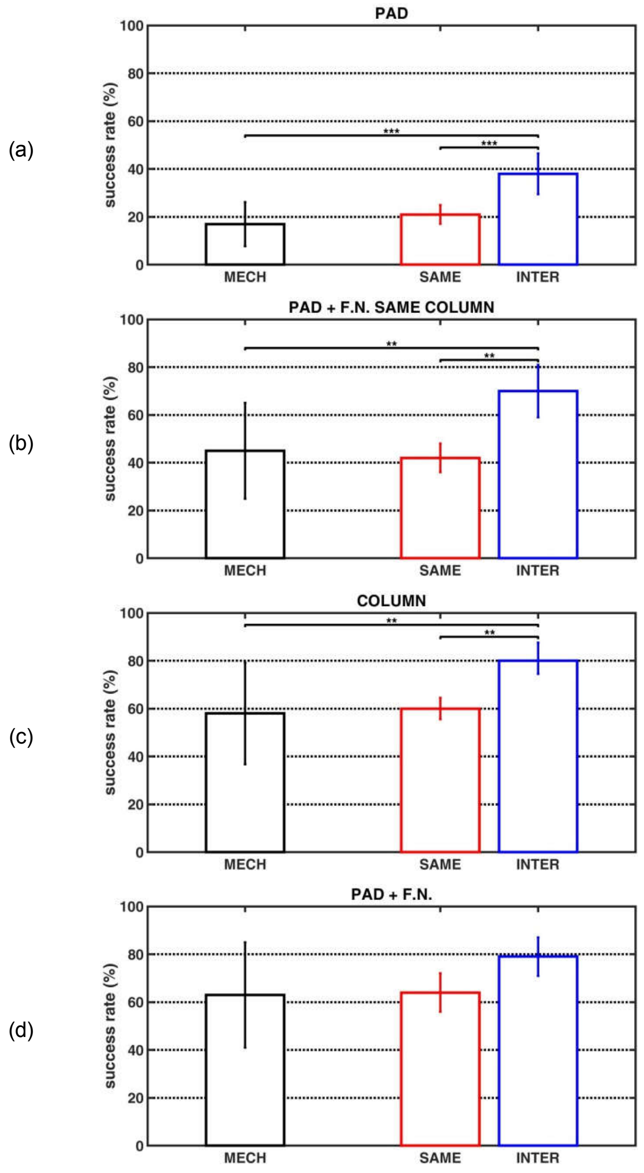

FIGURE 7. The summary results for all subjects (Sample size n = tested subjects = 8). Bars and stars indicated statistical significance (*, p<0.05; **, p<0.01; ***, p<0.001). The bars show the success rates (mean ± standard deviation) in identifying the right pad (a), pointing to the right pad or first neighbors (F.N.) within the same column (b), pointing to the right pad or any pad belonging to the same column (c) and pointing to the right pad or any of its first neighbors, regardless of the column (d).

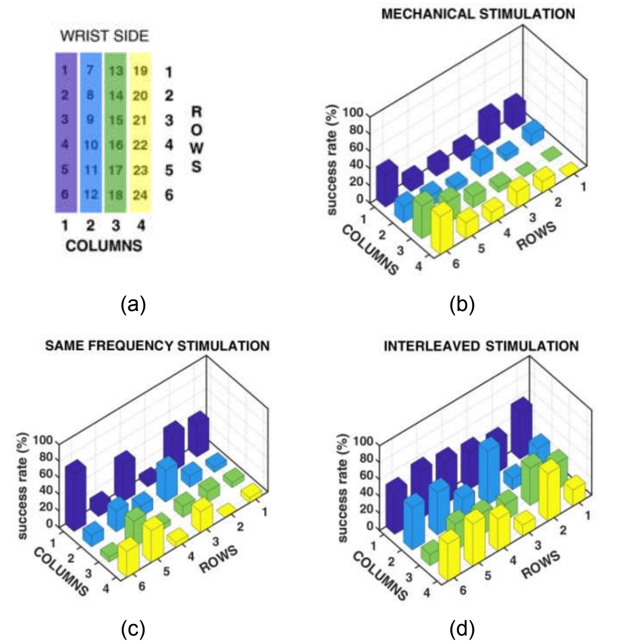

FIGURE 8. Success rates for the identification of each pad. The scheme reported in (a) illustrates the orientation of the matrix electrode with respect to the forearm.

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